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Miyagawa

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(54) **THREE-DIMENSIONAL MEASURING APPARATUS, THREE-DIMENSIONAL MEASURING METHOD, AND THREE-DIMENSIONAL MEASURING PROGRAM**

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G01B 11/30	(2006.01)
G06K 9/00	(2006.01)

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(58) **Field of Classification Search**
CPC G01B 11/002; G01B 11/2522; G01B 11/005; G01B 11/2545
USPC 356/602, 625; 382/154
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,589,942 A 12/1996 Gordon
6,028,672 A 2/2000 Geng

(Continued)

FOREIGN PATENT DOCUMENTS

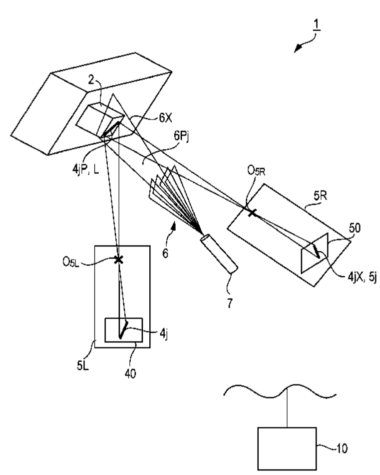
JP 2003-42735 A 2/2003
JP 2010065690 * 6/2011 .... G01B 11/25

Primary Examiner — Tarifur Chowdhury
Assistant Examiner — Sunghee Y Gray
(74) *Attorney, Agent, or Firm* — Canon USA Inc. IP Division

(57) **ABSTRACT**

A three-dimensional measuring apparatus **1** projects slit light from a projector **7** onto a work **2** and a stereo camera **5** captures an image of the work projected by the slit light. A control apparatus **10** of the three-dimensional measuring apparatus **1** temporarily identifies a correspondence between a bright line **4*j*** on a first image of the captured stereo image and a light-section plane **6**Pj and projects the bright line **4*j*** onto the light-section plane **6**Pj. The bright line projected onto the light-section plane **6**Pj is projected onto a second image. The control apparatus **10** calculates the level of similarity between a bright line **4*j*** X projected onto the second image and a bright line on the second image and determines a result of identified correspondence relationship between the bright line **4*j*** X and the bright line on the second image.

5 Claims, 14 Drawing Sheets



(51) **Int. Cl.**
G01B 11/25 (2006.01)
G01B 11/00 (2006.01)

(56) **References Cited**

U.S. PATENT DOCUMENTS

2004/0151365	A1	8/2004	An Chang	
2008/0249659	A1*	10/2008	Ueyama	700/245
2008/0319704	A1	12/2008	Forster	
2010/0322481	A1*	12/2010	Katano et al.	382/106
2011/0221891	A1*	9/2011	Sonoda	348/135
2012/0120412	A1*	5/2012	Bellis et al.	356/603
2013/0076857	A1*	3/2013	Kurashige et al.	348/40

* cited by examiner

FIG. 1

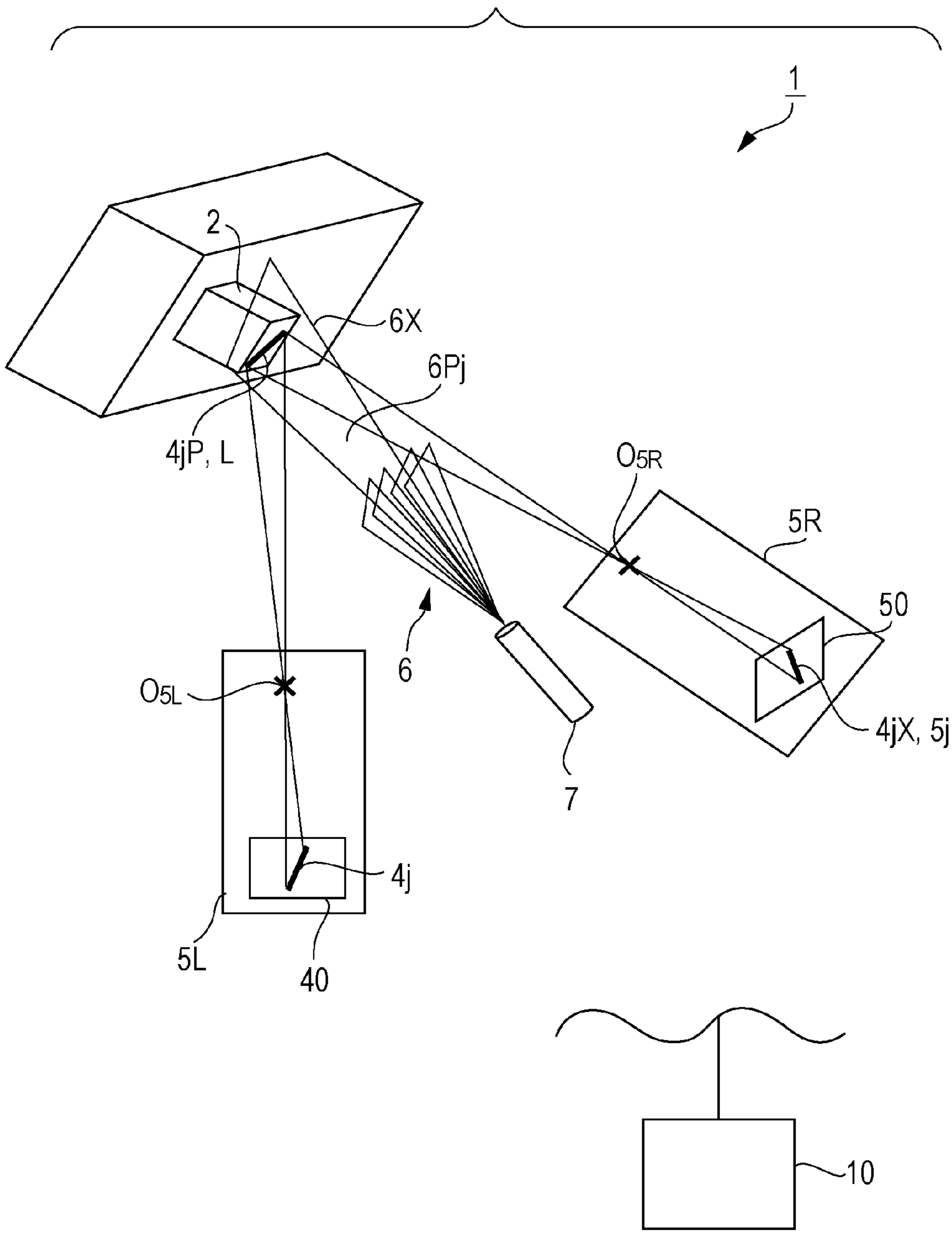


FIG. 2

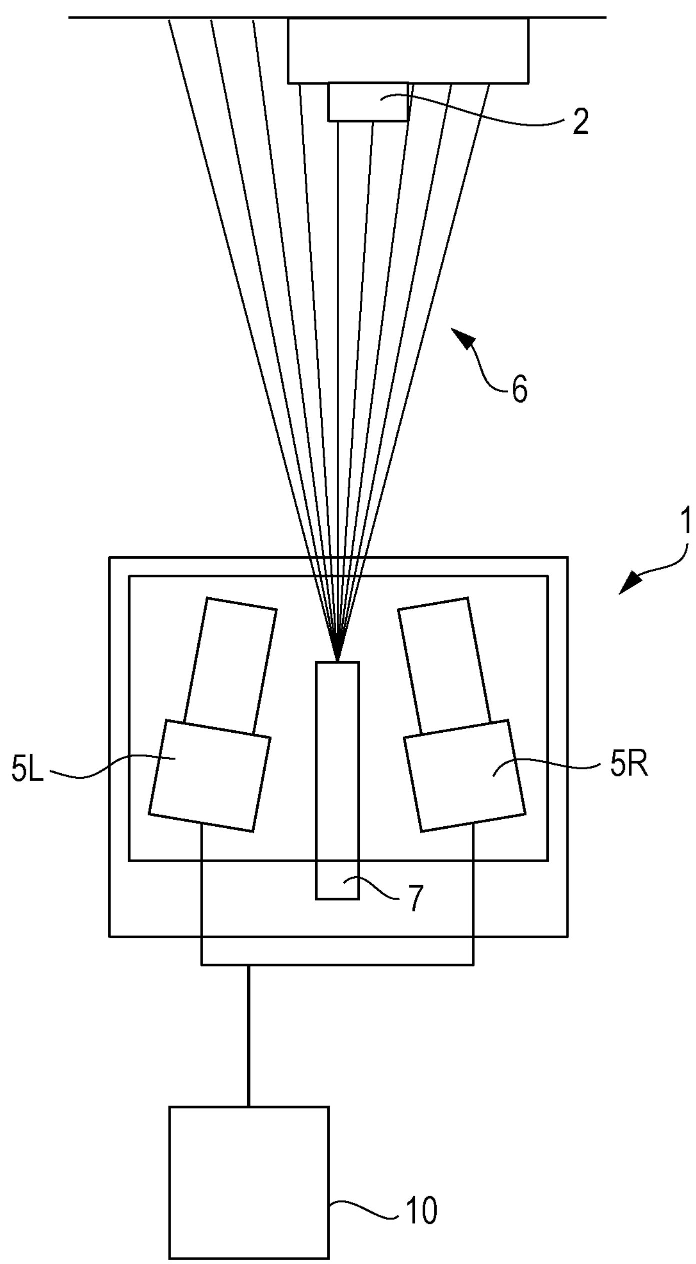


FIG. 3

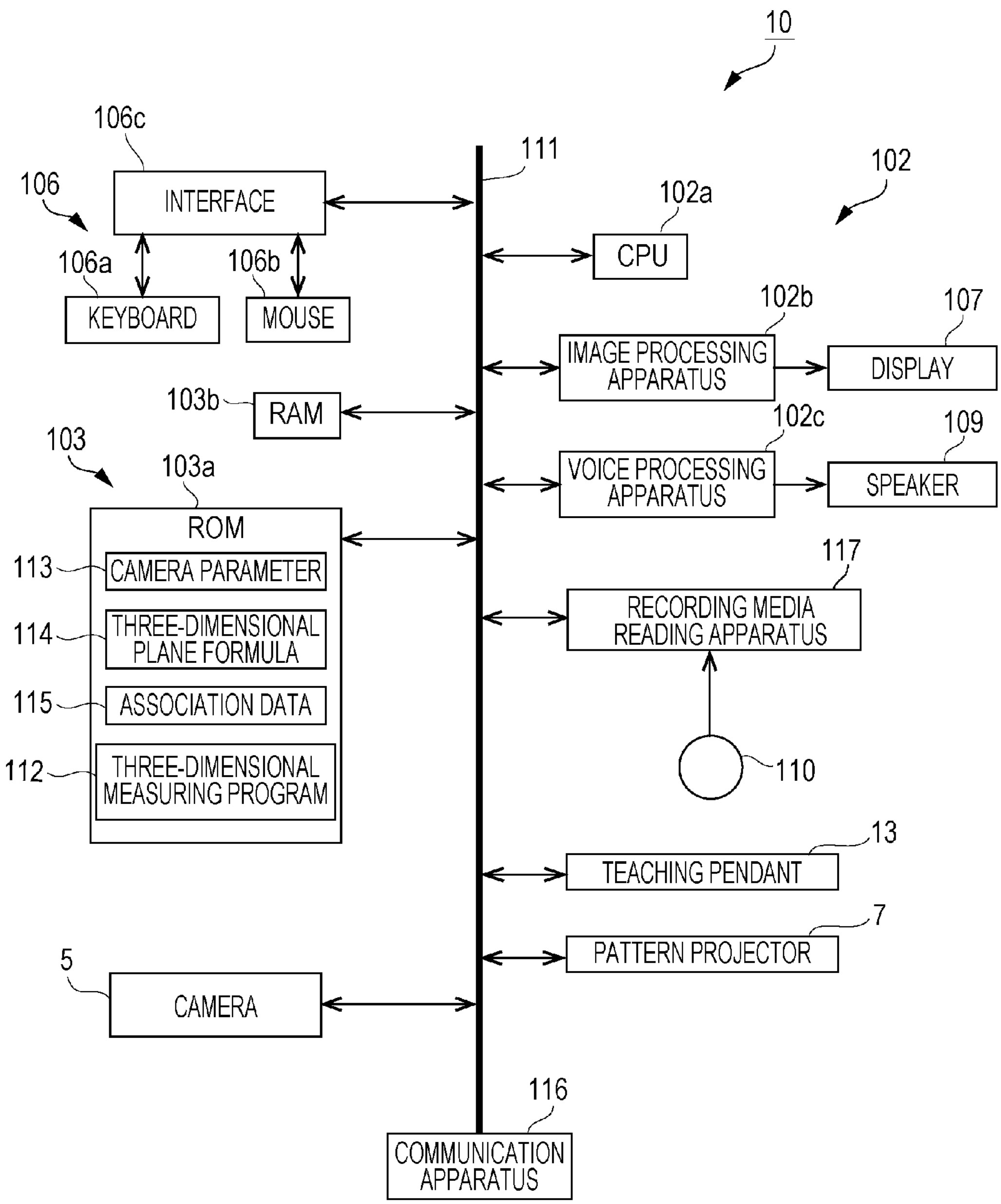

10
106c
INTERFACE
106
106a
KEYBOARD
106b
MOUSE
111
102
102a
CPU
102b
IMAGE PROCESSING APPARATUS
107
DISPLAY
103b
RAM
103
103a
ROM
113
CAMERA PARAMETER
114
THREE-DIMENSIONAL PLANE FORMULA
115
ASSOCIATION DATA
112
THREE-DIMENSIONAL MEASURING PROGRAM
102c
VOICE PROCESSING APPARATUS
109
SPEAKER
117
RECORDING MEDIA READING APPARATUS
110
13
TEACHING PENDANT
7
PATTERN PROJECTOR
5
CAMERA
116
COMMUNICATION APPARATUS

FIG. 4

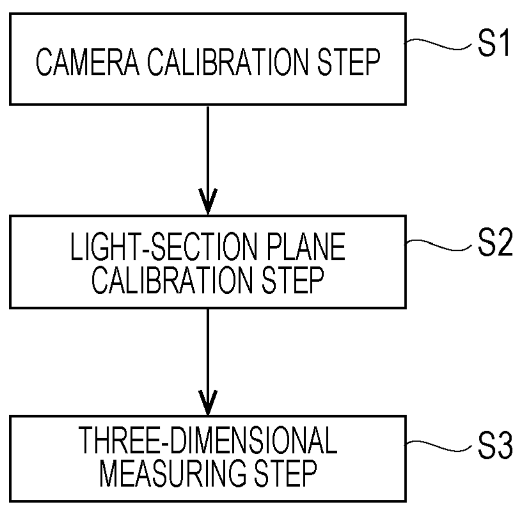

CAMERA CALIBRATION STEP
S1
LIGHT-SECTION PLANE CALIBRATION STEP
S2
THREE-DIMENSIONAL MEASURING STEP
S3

FIG. 5

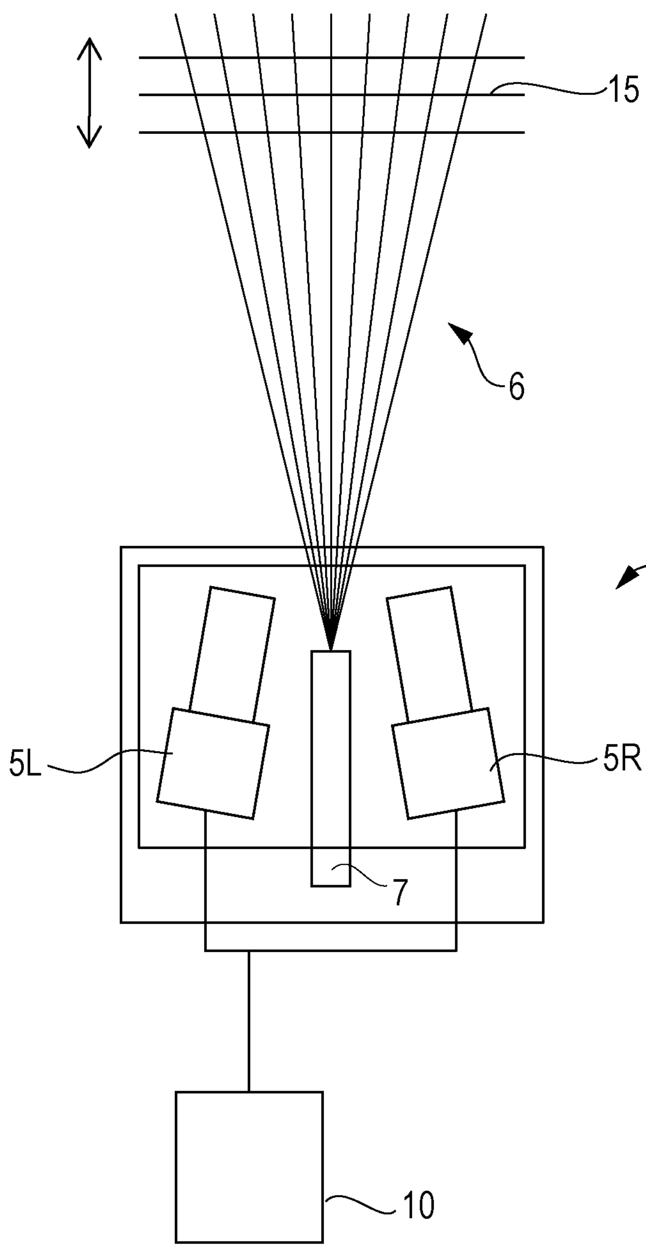


FIG. 6A

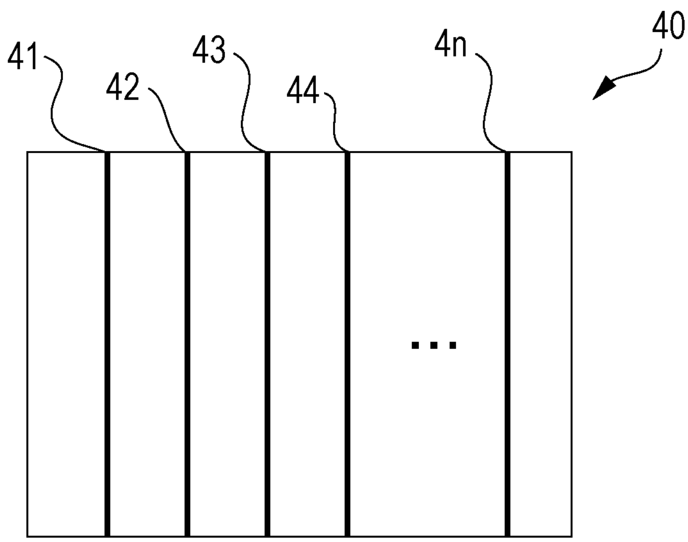


FIG. 6B

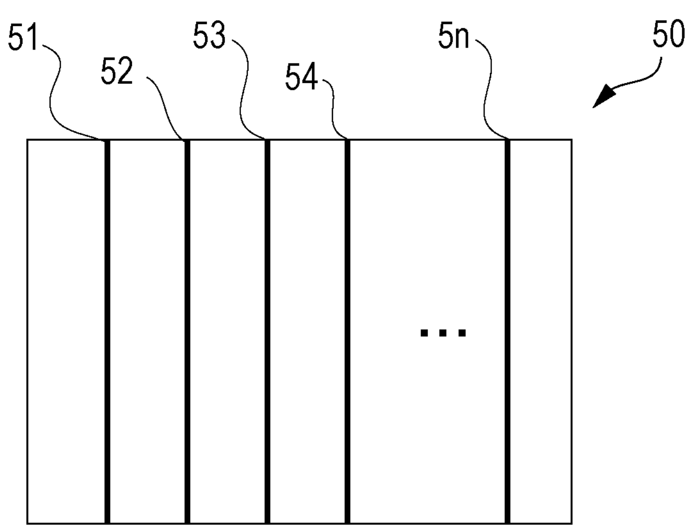


FIG. 7

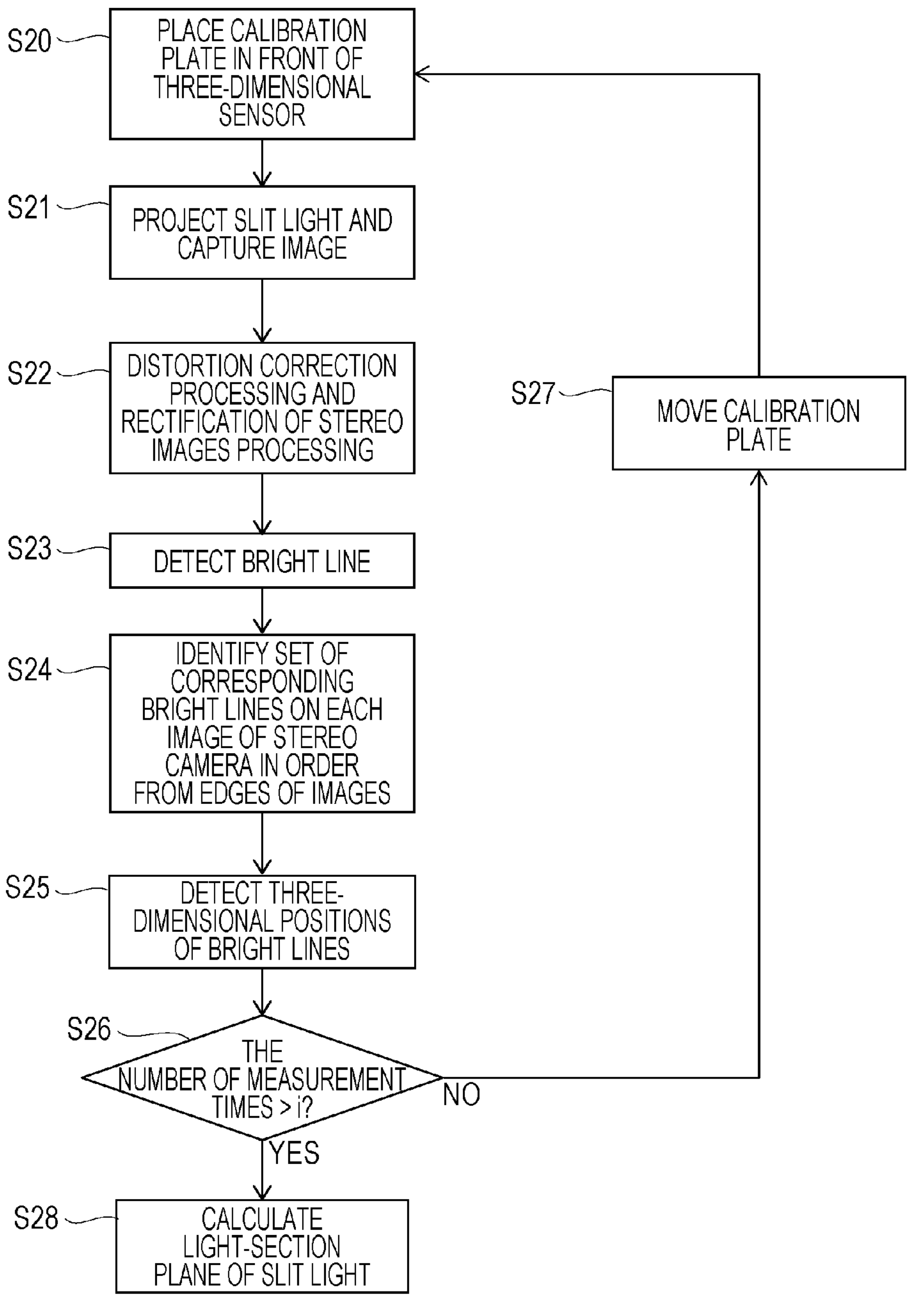

S20
PLACE CALIBRATION PLATE IN FRONT OF THREE-DIMENSIONAL SENSOR
S21
PROJECT SLIT LIGHT AND CAPTURE IMAGE
S22
DISTORTION CORRECTION PROCESSING AND RECTIFICATION OF STEREO IMAGES PROCESSING
S23
DETECT BRIGHT LINE
S24
IDENTIFY SET OF CORRESPONDING BRIGHT LINES ON EACH IMAGE OF STEREO CAMERA IN ORDER FROM EDGES OF IMAGES
S25
DETECT THREE-DIMENSIONAL POSITIONS OF BRIGHT LINES
S26
THE NUMBER OF MEASUREMENT TIMES > i?
NO
YES
S27
MOVE CALIBRATION PLATE
S28
CALCULATE LIGHT-SECTION PLANE OF SLIT LIGHT

FIG. 8

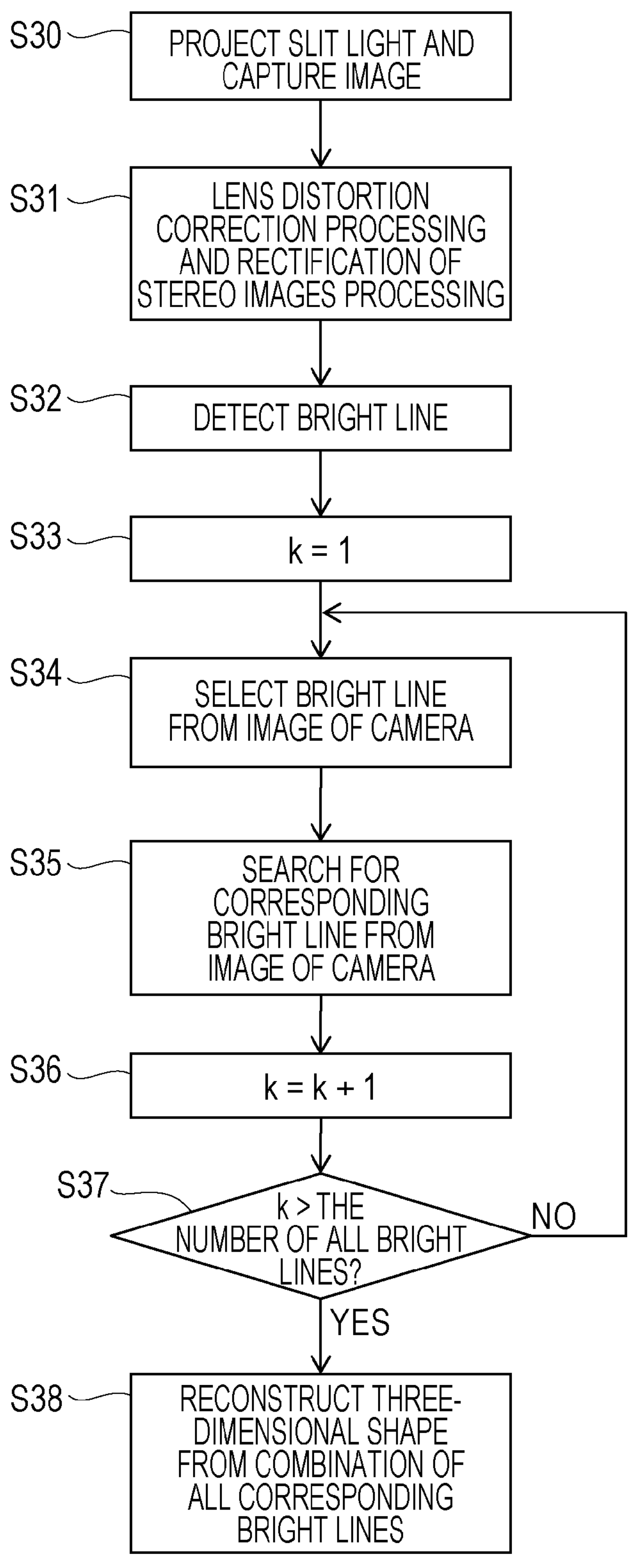

S30
PROJECT SLIT LIGHT AND CAPTURE IMAGE
S31
LENS DISTORTION CORRECTION PROCESSING AND RECTIFICATION OF STEREO IMAGES PROCESSING
S32
DETECT BRIGHT LINE
S33
k = 1
S34
SELECT BRIGHT LINE FROM IMAGE OF CAMERA
S35
SEARCH FOR CORRESPONDING BRIGHT LINE FROM IMAGE OF CAMERA
S36
k = k + 1
S37
k > THE NUMBER OF ALL BRIGHT LINES?
NO
YES
S38
RECONSTRUCT THREE-DIMENSIONAL SHAPE FROM COMBINATION OF ALL CORRESPONDING BRIGHT LINES

FIG. 9

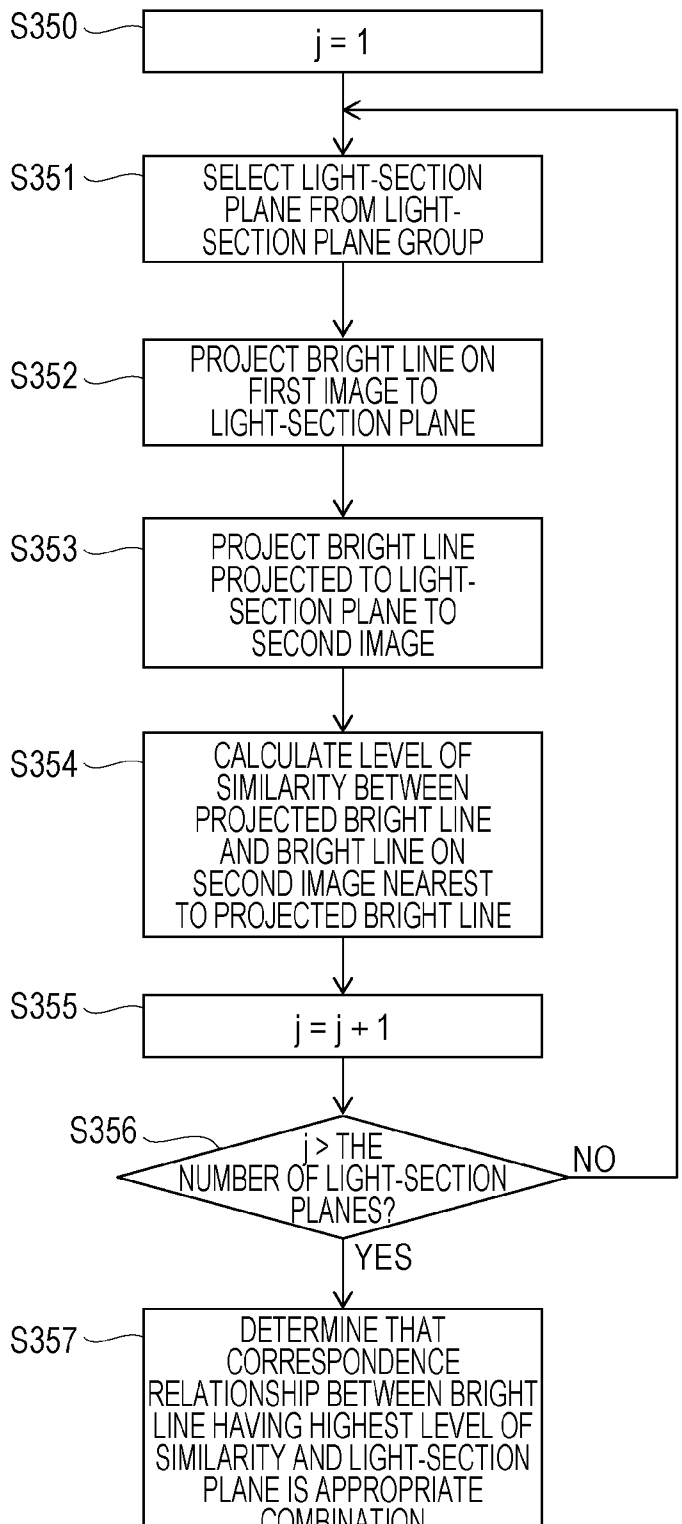

S350
j = 1
S351
SELECT LIGHT-SECTION PLANE FROM LIGHT-SECTION PLANE GROUP
S352
PROJECT BRIGHT LINE ON FIRST IMAGE TO LIGHT-SECTION PLANE
S353
PROJECT BRIGHT LINE PROJECTED TO LIGHT-SECTION PLANE TO SECOND IMAGE
S354
CALCULATE LEVEL OF SIMILARITY BETWEEN PROJECTED BRIGHT LINE AND BRIGHT LINE ON SECOND IMAGE NEAREST TO PROJECTED BRIGHT LINE
S355
j = j + 1
S356
j > THE NUMBER OF LIGHT-SECTION PLANES?
NO
YES
S357
DETERMINE THAT CORRESPONDENCE RELATIONSHIP BETWEEN BRIGHT LINE HAVING HIGHEST LEVEL OF SIMILARITY AND LIGHT-SECTION PLANE IS APPROPRIATE COMBINATION

FIG. 10

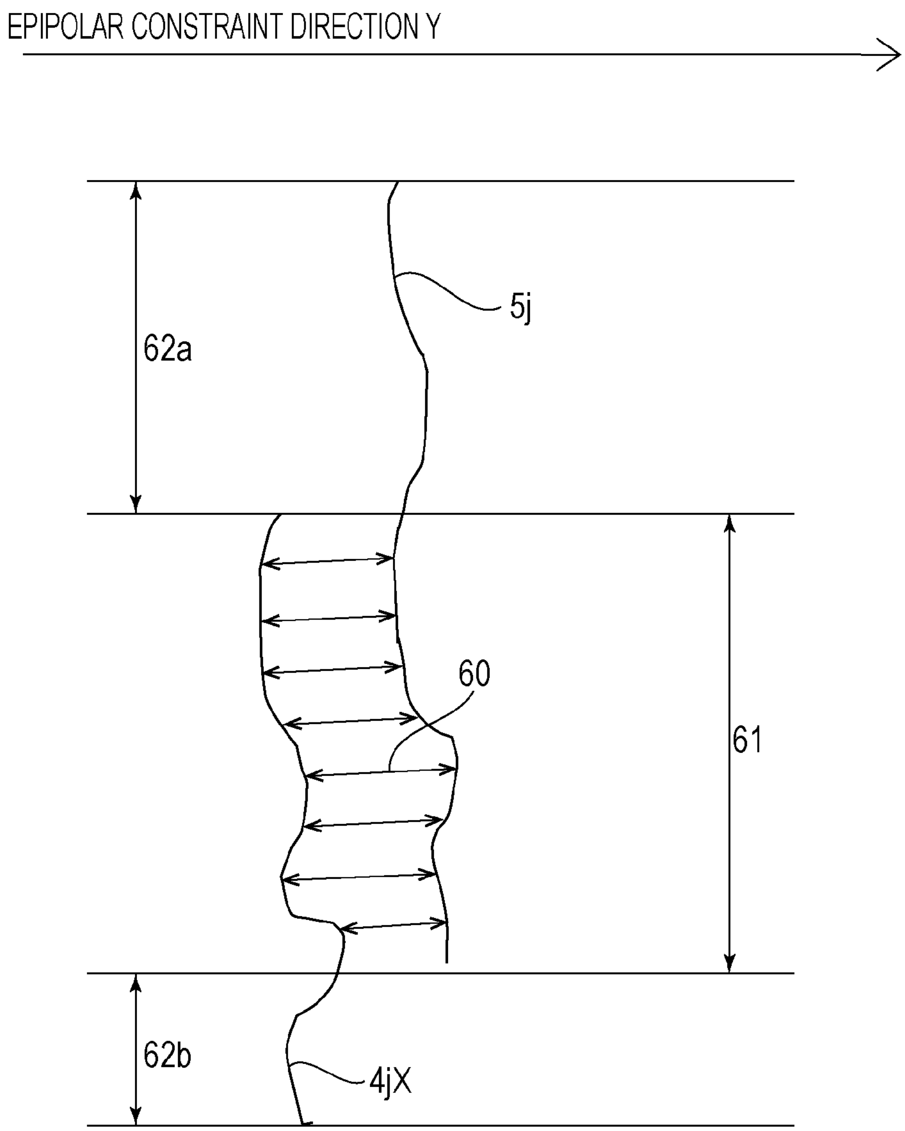


FIG. 11

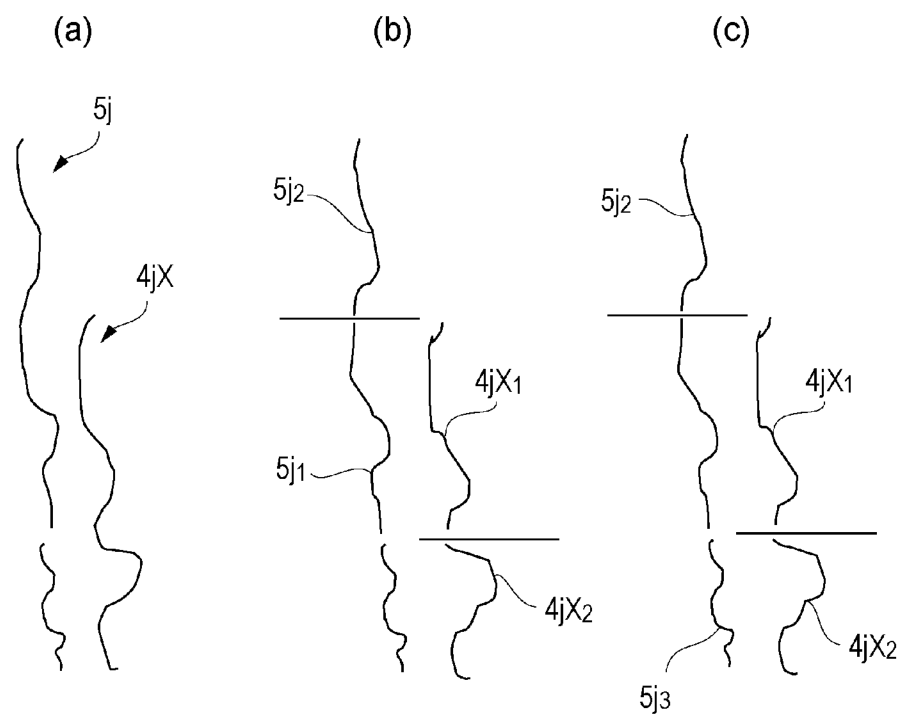


FIG. 12

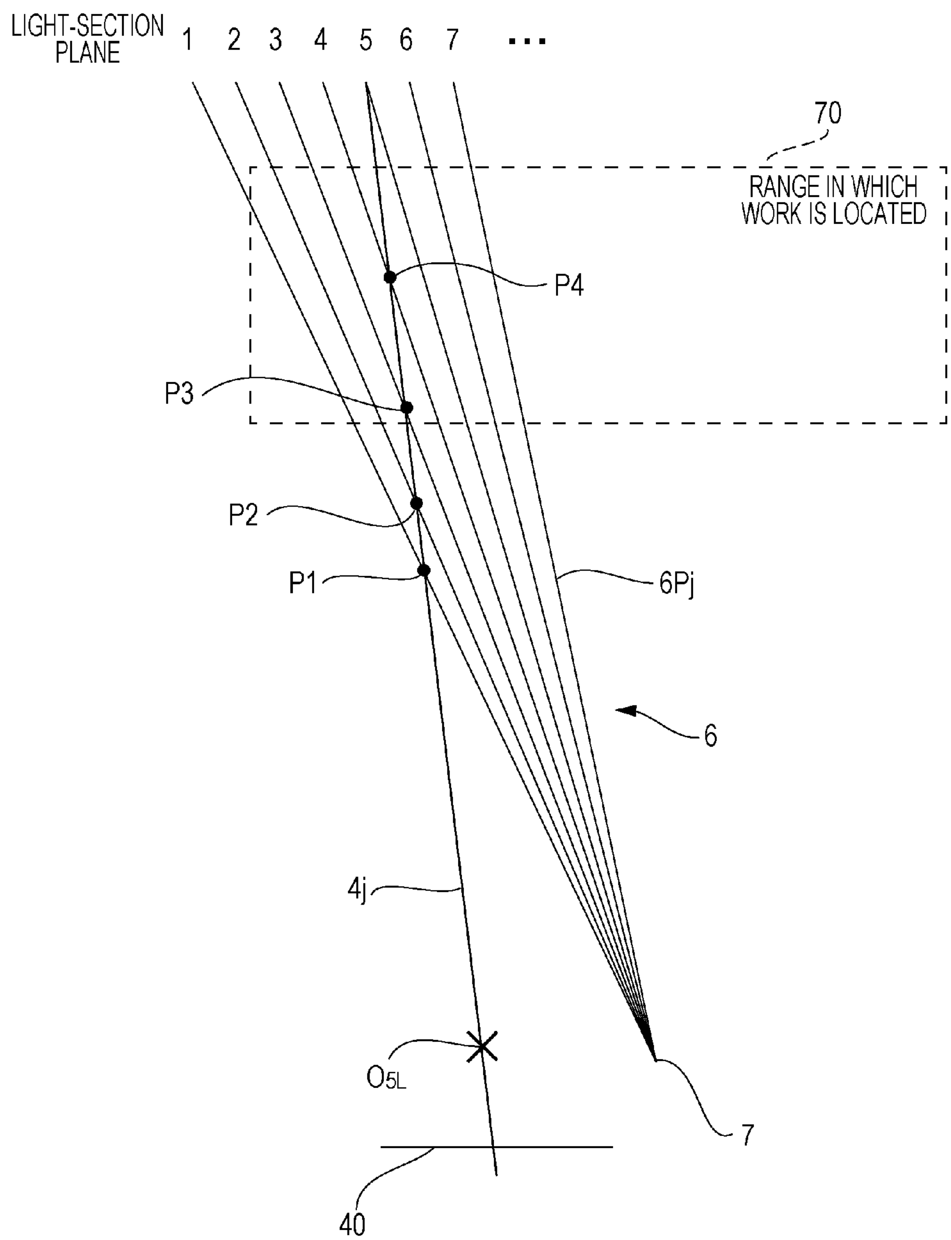

LIGHT-SECTION PLANE
1 2 3 4 5 6 7 ...
70
RANGE IN WHICH WORK IS LOCATED
P4
P3
P2
P1
6Pj
6
4j
O5L
7
40

FIG. 13

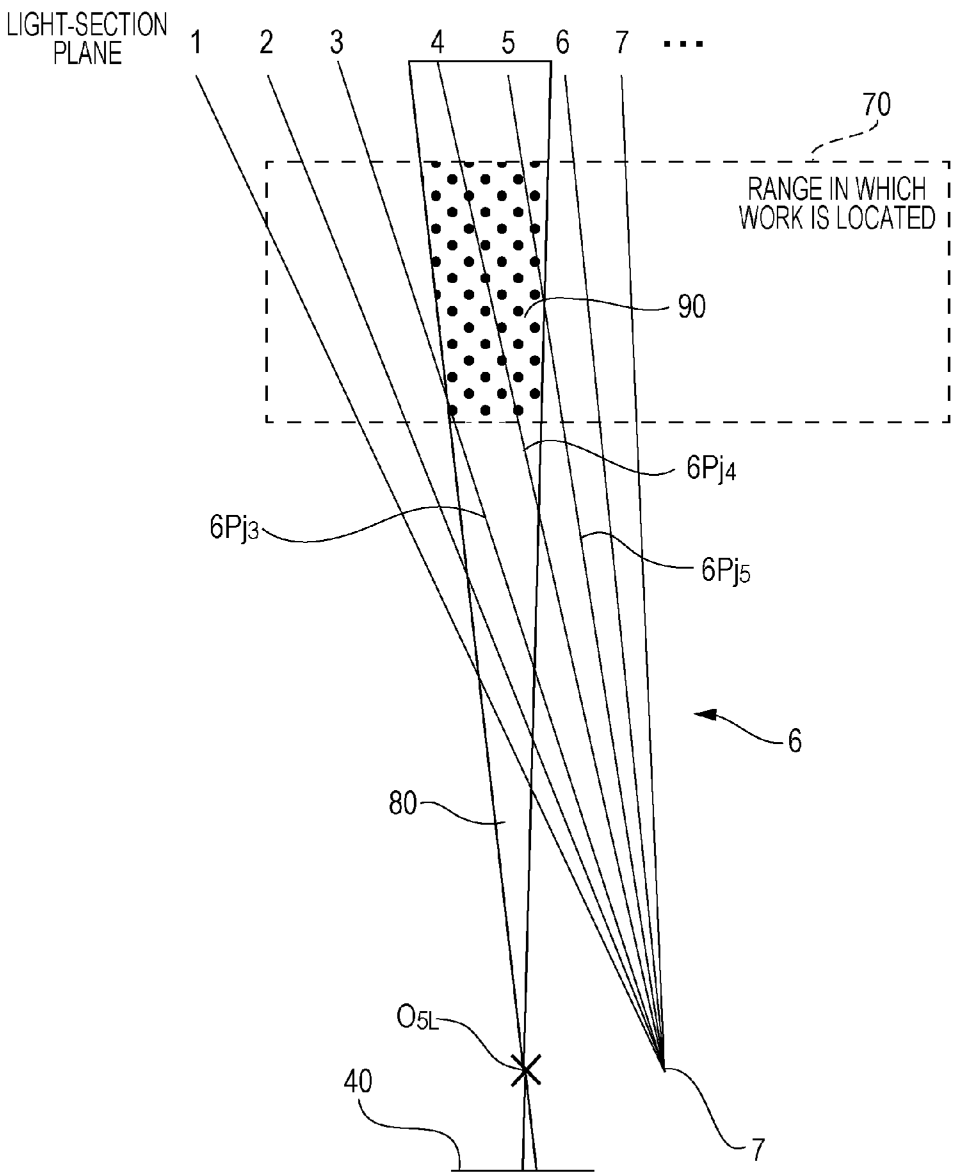

LIGHT-SECTION PLANE
1
2
3
4
5
6
7
...
70
RANGE IN WHICH WORK IS LOCATED
90
6Pj4
6Pj3
6Pj5
6
80
O5L
40
7

FIG. 14A

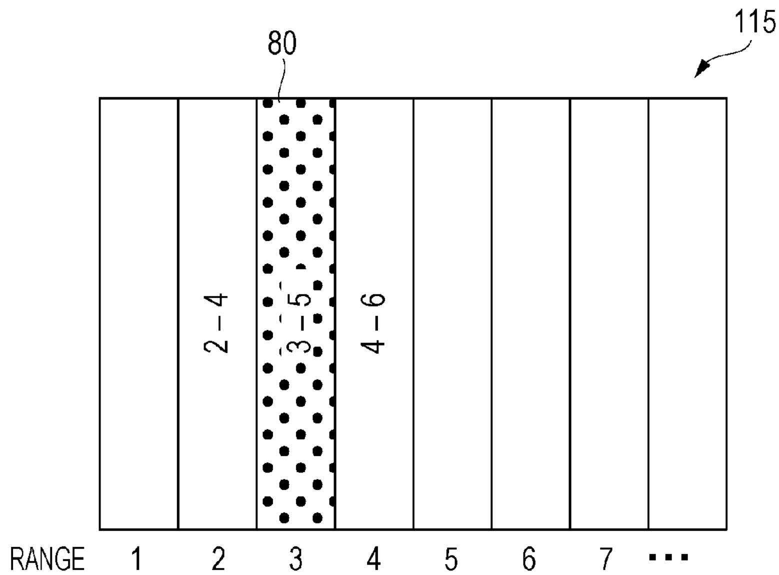
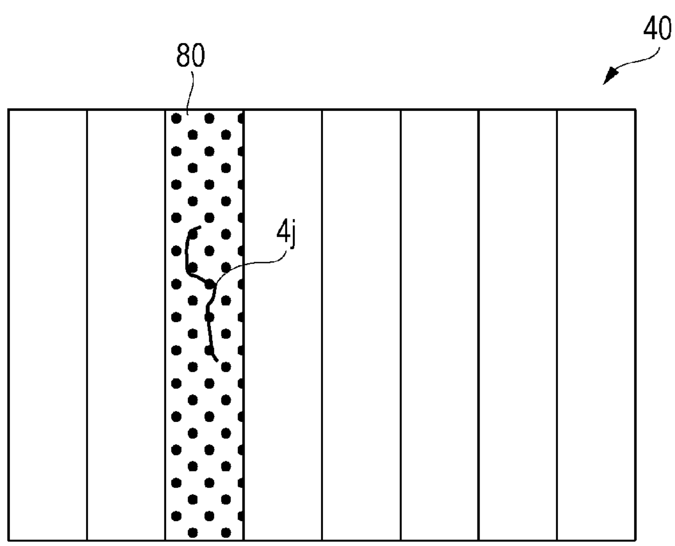


FIG. 14B



THREE-DIMENSIONAL MEASURING APPARATUS, THREE-DIMENSIONAL MEASURING METHOD, AND THREE-DIMENSIONAL MEASURING PROGRAM

CROSS REFERENCE TO RELATED APPLICATIONS

This application is a National Stage filing of International Application No. PCT/JP2013/001944 filed Mar. 22, 2013, which claims the benefit of priority from Japanese Patent Application No. 2012-079950 filed Mar. 30, 2012, the disclosures of each of which are hereby incorporated by reference herein in their entirety.

TECHNICAL FIELD

The present invention relates to a three-dimensional measuring in which a projector projects slit light onto an object to be measured and a captured image of the object to be measured which is projected by the slit light is used.

BACKGROUND ART

A stereo method that uses the principle of triangulation is well known to three-dimensionally measure an object to be measured (hereinafter, simply referred to as a "work") from an image captured by a camera. In the stereo method, generally, an image of the work is captured by a stereo camera that has been calibrated and the work is three-dimensionally measured by using the disparity between left and the right cameras.

On the other hand, when the contrast of the work is low, such as in a case of an uneven portion of a black work, it is known that a light-section method which is a type of the stereo method can be used. In the light-section method, a projector projects slit light onto the work and a three-dimensional measuring is performed by using a captured image of the work which is projected by the slit light. More specifically, in the light-section method, a three-dimensional plane equation of a light-section plane of the slit light to be projected is obtained in advance and an image of a bright line on the work projected by the slit light is captured by a camera. Then, the three-dimensional measuring is performed on the basis of the principle of triangulation from the position of the bright line on the obtained image and the three-dimensional plane equation of the light-section plane obtained in advance.

By the way, in the light-section method, if the number of the slit lights projected from the projector is one, when measuring the entire shape of the work, an image of the work has to be captured a plurality of times while moving the work or the slit light. Therefore, conventionally, a three-dimensional measuring apparatus which projects a plurality of slit lights at the same time from a projector is proposed (see PTL 1) so that the number of times of the image capturing is small when performing the three-dimensional measuring of the work.

Here, when a plurality of slit lights are projected onto the work, to perform the three-dimensional measuring, it is necessary to identifies a correspondence between each of a plurality of bright lines on the captured image and a plurality of light-section planes. Therefore, the three-dimensional measuring apparatus described in PTL 1 uses a color light source in the projector and sequentially changes colors of the bright lines so that the colors of adjacent bright lines (slit lights) are different from each other. The image of the bright lines having different colors is captured by a camera, so that the bright

lines and the light-section planes correspond to each other on the basis of the colors of the bright lines.

CITATION LIST

Patent Literature

PTL 1: Japanese Patent Laid-Open No. 2003-42735

SUMMARY OF INVENTION

Technical Problem

However, in the three-dimensional measuring method that identifies a correspondence between the bright lines on the image and the light-section planes by the colors of the bright lines as in the PTL 1, a color light source and a color camera are inevitably required. Therefore, there is a problem that this method cannot be applied to a three-dimensional measuring apparatus that uses a monochrome camera. Also there is a problem that the measurement accuracy is easily affected by the color of the surface of the work because as the number of the colors of the slit light increases, it is necessary to distinguish subtle differences among the colors from the image.

Therefore, the present invention provides a three-dimensional measuring apparatus and a three-dimensional measuring method that can identify a correspondence between the bright lines on the image and the light-section planes by a method different from the method of distinguishing the bright lines by color.

Solution to Problem

The present invention provides a three-dimensional measuring apparatus including a projector that projects slit light onto a work, a first camera that captures an image of the work projected by the slit light, a second camera that captures an image of the work projected by the slit light from a position different from that of the first camera, and a control apparatus that stores a three-dimensional plane equation of a light-section plane of the slit light, identifies a correspondence among a bright line generated on a first image captured by the first camera by projecting the slit light, a bright line generated on a second image captured by the second camera by projecting the slit light, and the three-dimensional plane equation of the light-section plane with each other, and performs three-dimensional measuring of the work by a principle of triangulation by using a correspondence relationship between any of the bright line on the first image, the bright line on the second image, and the light-section plane. The control apparatus temporarily identifies a correspondence between the bright line on the first image and the light-section plane, temporarily projects the bright line on the first image onto the light-section plane in a three-dimensional virtual space, and thereafter projects the bright line onto the second image captured by the second camera through the light-section plane, and identifies a correspondence between the light-section plane and the bright lines on the images of the first and the second cameras on the basis of a level of similarity between the bright line on the first image which is projected onto the second image and the bright line on the second image.

The present invention provides a three-dimensional measuring method in which slit lights are projected from a projector onto a work and three-dimensional measuring of the work is performed by using a captured image of the work projected by the slit lights and three-dimensional plane equations of light-section planes of the plurality of slit lights. The three-dimensional measuring method includes an image acquisition step in which an arithmetic unit acquires a first image and a second image of the work projected by the plurality of slit lights, which are captured from different positions, a step of identifying a set of corresponding bright lines in which the arithmetic unit temporarily identifies a correspondence between each bright line on the first image and one of the light-section planes of the plurality of slit lights, temporarily projects the bright line on the first image onto the corresponding light-section plane in a three-dimensional virtual space, and thereafter projects the bright line onto the second image through the light-section plane, determines whether or not the light-section plane and the bright lines on the first and the second images appropriately correspond to each other on the basis of a level of similarity between the bright line on the first image which is projected onto the second image and the bright line on the second image, and determines a correspondence among each bright line on the first and the second images and the light-section planes, and a measuring step in which the arithmetic unit performs three-dimensional measuring of the work by a principle of triangulation by using a correspondence relationship between any of the bright line on the first image, the bright line on the second image, and the light-section planes.

Advantageous Effects of Invention

According to the present invention, it is possible to project the bright line on the first image onto the second image through a temporarily selected light-section plane and identifies a correspondence between a light-section plane and a bright line on an image on the basis of the level of similarity between the projected bright line and the bright line on the second image.

BRIEF DESCRIPTION OF DRAWINGS

FIG. **1** is a schematic diagram showing a three-dimensional measuring apparatus according to an embodiment of the present invention.

FIG. **2** is a plan view of FIG. **1**.

FIG. **3** is a block diagram showing a control apparatus according to the embodiment of the present invention.

FIG. **4** is a flowchart showing a three-dimensional measuring method according to the embodiment of the present invention.

FIG. **5** is a schematic diagram showing the three-dimensional measuring apparatus in a light-section plane calibration step.

FIG. **6**A is a diagram showing an image captured by a first camera in the light-section plane calibration step.

FIG. **6**B is a diagram showing an image captured by a second camera in the light-section plane calibration step.

FIG. **7** is a flowchart showing the light-section plane calibration step.

FIG. **8** is a flowchart showing a three-dimensional measuring step.

FIG. **9** is a flowchart showing a step of identifying a set of corresponding bright lines.

FIG. **10** is a schematic diagram for explaining a calculation method of a level of similarity of bright lines.

FIG. **11** is a schematic diagram for explaining a division method of bright lines, (a) is a diagram showing a state in which a correspondence between the bright lines is identified, (b) is a diagram showing a state in which the bright lines are divided, and (c) is a diagram showing a state in which a correspondence between newly divided bright lines is identified.

FIG. **12** is a schematic diagram showing a method for determining light-section planes where the level of similarity is calculated.

FIG. **13** is a schematic diagram showing a method for selecting a light-section plane whose correspondence with the bright line is identified.

FIG. **14**A is a diagram showing a light-section plane search image.

FIG. **14**B is a diagram showing a correspondence relationship between the light-section plane search image and a first image.

DESCRIPTION OF EMBODIMENT

Hereinafter, a three-dimensional measuring apparatus **1** according to an embodiment of the present invention will be described with reference to the drawings.

Configuration of Three-Dimensional Measuring Apparatus

As shown in FIGS. **1** and **2**, the three-dimensional measuring apparatus **1** that performs three-dimensional measuring of a work **2** includes a stereo camera **5** that captures an image of the work **2** and a pattern projector **7** that projects multi-slit light **6** onto the work **2**. The three-dimensional measuring apparatus **1** also includes a control apparatus **10** to which the stereo camera **5** and the pattern projector **7** is connected.

The stereo camera **5** includes a first camera **5**L and a second camera **5**R which are monochrome cameras and the pattern projector **7** is configured to project a plurality of single color slit lights **6** onto the work **2** and form a simple stripe pattern on the work. The stereo camera **5** and the pattern projector **7** are disposed so that the visual fields of the first camera **5**L and the second camera **5**R and a projection range of the pattern projector **7** overlap each other. The work **2** is placed at a position where the visual fields of the camera **5** and the projection range overlap each other. More specifically, the second camera **5**R is disposed opposite to the first camera **5**L with the pattern projector **7** in between. The first camera **5**L and the second camera **5**R are disposed so that their positions are different from each other. Further, the pattern projector **7** is oriented so that the multi-slit light **6** is perpendicular to the epipolar constraint of the stereo camera **5**.

As shown in FIG. **3**, the control apparatus **10** is configured so that the stereo camera **5** and the pattern projector **7** are connected to a computer main body including an arithmetic unit **102** and a storage apparatus **103**. Also an input apparatus **106** for an operator to perform an input operation, a teaching pendant **13**, and a display apparatus **107** are connected to the computer main body.

The storage apparatus **103** stores a camera parameter **113** of the stereo camera **5**, data **114** of a three-dimensional plane equation of a light-section plane **6**Pj of each of the plurality of slit lights **6**, candidate index data **115** of the light-section plane **6**Pj described later in detail, and the like. Further, the storage apparatus **103** stores various programs such as a control driver of the stereo camera **5** and a three-dimensional measuring program **112** that causes the computer to perform the three-dimensional measuring of the work **2**. The camera parameter **113** is a parameter that represents a focal length and a distortion of a lens and a positional relationship between the cameras.

More specifically, the computer main body includes a CPU **102**_a_ as a main component, an image processing apparatus **102**_b_, and a voice processing apparatus **102**_c_ to form the arithmetic unit **102**. In addition to the image processing apparatus **102***b* and the voice processing apparatus **102***c*, a ROM **103***a* and a RAM **103***b* are connected to the CPU **102***a* through a bus **111**. The ROM **103***a* stores a program necessary for basic control of the computer as well as various programs such as the above-described three-dimensional measuring program **112** and data. In the RAM **103***b*, a work area of the CPU **102***a* is secured. The image processing apparatus **102***b* controls a liquid crystal display functioning as the display apparatus **107** according to a drawing instruction from the CPU **102***a* and causes the liquid crystal display to display a predetermined image on a screen thereof. The voice processing apparatus **102***c* generates an audio signal according to a voice generation instruction from the CPU **102***a* and outputs the audio signal to a speaker **109**.

A keyboard **106***a* and a mouse **106***b* which function as the input apparatus **106** are connected to the CPU **102***a* through an input interface **106***c* connected to the bus **111**, so that it is possible to input specification information necessary to perform the three-dimensional measuring of the work **2** and other instructions.

In addition to the stereo camera **5** and the pattern projector **7**, a recording media reading apparatus **117** is connected to the bus **111**. Therefore, it is possible to read a recording medium **110** storing the three-dimensional measuring program **112** and the like by the recording media reading apparatus **117** and store the three-dimensional measuring program **112** and the like into, for example, the ROM **103***a*. The above-described storage apparatus **103** includes another external storage apparatus in addition to the ROM **103***a* and the RAM **103***b* which are a main storage apparatus.

Further, a communication apparatus **116** is connected to the bus **111**, so that it is possible to download the three-dimensional measuring program **112** delivered from the Internet or the like through the communication apparatus **116** without using the recording medium **110** described above.

In the present embodiment, the control apparatus **10** is configured by a computer to which the stereo camera **5** is connected. However, the control apparatus **10** may be configured in cooperation with an arithmetic unit included in the stereo camera **5** or may be configured by only the arithmetic unit included in the stereo camera **5**.

Operation of Three-Dimensional Measuring

Next, the three-dimensional measuring of the work **2** based on the three-dimensional measuring program **112** will be described. As shown in FIG. **4**, the three-dimensional measuring of the work **2** includes an advance preparation stage including a camera calibration step (S**1** in FIG. **4**) and a light-section plane calibration step (S**2** in FIG. **4**) and an actual three-dimensional measuring step (S**3** in FIG. **4**). In the description below, first, the camera calibration step S**1** and the light-section plane calibration step S**2** will be described, and thereafter, the three-dimensional measuring step S**3** will be described.

When performing the three-dimensional measuring of the work **2**, first, the three-dimensional measuring apparatus **1** calibrates the stereo camera **5** (camera calibration step). Specifically, an image of a camera calibration board including a plurality of markers is captured by the stereo camera **5**. Since a positional relationship of the markers of the calibration board is measured in advance, the control apparatus **10** of the three-dimensional measuring apparatus **1** compares positions of the markers on the captured stereo image with stored positions of the markers to calibrate the camera parameter **113** of the stereo camera **5** and stores the calibrated camera parameter **113**.

In other words, the control apparatus **10** functions as a camera parameter calibration unit that calibrates the camera parameter **113** of the stereo camera **5**. To calibrate the camera, an existing method is used (for example, Zhengyou Zhang. A flexible new technique for camera calibration. IEEE Transactions on Pattern Analysis and Machine Intelligence, Vol. 22, No. 11, pp. 1330-1334, 2000.).

When the calibration of the camera parameter **113** is completed, next, as shown in FIGS. **5** to **7**, the three-dimensional measuring apparatus **1** calibrates the light-section plane **6**Pj for each of a plurality of slit lights **6** (light-section plane calibration step). Specifically, as shown in FIG. **5**, first, a calibration plate **15** which is used to calibrate the light-section plane and which has a plain single color such as black is placed instead of the work **2** (S**20** in FIG. **7**). Further, the multi-slit light **6** is projected from the pattern projector onto the calibration plate **15** and an image of the calibration plate is captured by the stereo camera **5** (S**21** in FIG. **7**).

Next, the image captured by the stereo camera **5** is transmitted to the control apparatus **10** and distortion correction processing and stereo images rectification processing are performed by the control apparatus **10** using the camera parameter **113** (S**22** in FIG. **7**). Specifically, the control apparatus **10** functions as a distortion correction—rectification of stereo images processing unit and corrects images **40** and **50** captured by the stereo camera **5** by using the camera parameter **113** as if the images were captured by the stereo camera **5** which has no lens distortion and in which the left and the right cameras are arranged in parallel. Thereby, in the images **40** and **50** of the first and the second cameras, a line (epipolar line) including a point on one image corresponding to a point on the other image is a line in parallel with the X axis on the same Y coordinate, so that a corresponding point is easily detected.

When the correction processing of the captured images is performed, the control apparatus **10** functions as a bright line detection unit and detects a bright lines **4***n* and **5***n* formed when the multi-slit light **6** is projected onto the calibration plate **15** from the images **40** and **50** on which the distortion correction processing and the stereo images rectification processing are performed (S**23** in FIG. **7**).

The pattern projector **7** is arranged to be perpendicular to the epipolar constraint of the stereo camera **5**, so that the bright lines **4***n* and **5***n* have an angle near perpendicular to the epipolar line. Therefore, if the images are corrected by the distortion correction—rectification of stereo images processing unit, it is possible to detect points that form the bright lines **4***n* and **5***n* by detecting a peak from intensities of each pixel along the epipolar line, which is the X axis. Or, the points that form the bright lines may be detected by using a method such as binarization. After the points that form the bright lines are detected, the bright lines **4***n* and **5***n* can be detected by grouping the points adjacent to each other that form the bright lines. A too short bright line may be removed as noise by filtering the bright lines **4***n* and **5***n* detected here by the length thereof.

When the control apparatus **10** detects the bright lines **4***n* and **5***n* from the stereo images **40** and **50**, as shown in FIGS. **6**A and **6**B, the control apparatus **10** assumes that the visual field of the stereo camera **5** is one plane. The control apparatus **10** identifies a set of corresponding bright lines **4***n* and **5***n* on the images captured by the stereo camera **5** between the cameras (S**24** in FIG. **7**). Specifically, by using the number of slits of the multi-slit light **6** and a fact that the calibration plate **15** is a plane, the control apparatus **10** identifies a set of corresponding bright lines **4***n* and **5***n* on the first and the second images of the stereo camera **5** in order from the edges of the images.

When a set of corresponding bright lines **4***n* and **5***n* is identified, the control apparatus **10** functions as a three-dimensional reconstruction unit and detects three-dimensional positions of the bright lines formed when the multi-slit light **6** is projected onto the calibration plate **15** (S**25** in FIG. **7**). In other words, the control apparatus **10** obtains the three-dimensional position of the bright line by a stereo method from the correspondence relationship between the bright line **4***n* on the first image and the bright line **5***n* on the second image by using the camera parameter **113**.

When the three-dimensional position of the bright line is obtained, the control apparatus **10** determines whether or not the number of measurement times of the three-dimensional position of the bright line is greater than or equal to a predetermined number of measurement times i (S**26** in FIG. **7**). When the number of measurement times is smaller than the predetermined number of times i (NO in S**26** in FIG. **7**), the control apparatus **10** moves the position of the calibration plate **15** in the depth direction of the stereo camera **5** (S**27** in FIG. **7**) and repeats the process of steps S**20** to S**25** to measure again the three-dimensional position of the bright line.

On the other hand, when the number of measurement times is greater than or equal to the predetermined number of times i (YES in S**26** in FIG. **7**), the control apparatus **10** calculates the three-dimensional plane equation of the light-section plane **6**Pj of each slit light **6**X from the measurement result of the three-dimensional position of the bright line and stores the three-dimensional plane equation (S**28** in FIG. **7**). In other words, the bright line formed on the calibration plate by the multi-slit light **6** is present on the light-section plane of the multi-slit light **6**. Therefore, the three-dimensional positions of the bright lines measured while moving the calibration plate **15** are present on the same plane for each slit and the control apparatus **10** calculates an approximate plane by collecting the three-dimensional positions of the bright lines obtained by a plurality of measurements for each slit, so that the control apparatus **10** obtains the three-dimensional plane equation.

When the camera calibration step S**1** and the light-section plane calibration step S**2** described above are completed, the advance preparation of the measurement of the three-dimensional measuring apparatus **1** is completed, so that it is possible to perform the three-dimensional measuring. The positional relationship among the first camera **5**L, the second camera **5**R, and the projector **7** is determined as described above. The bright line generated on or near the plane represented by the three-dimensional plane equation corresponding to the slit light projected by the projector **7** corresponds to an image of the bright line captured by the first camera **5**L or an image of the bright line captured by the second camera **5**R. Since the three-dimensional plane equation is determined corresponding to the slit light, as described later in detail, it is possible to easily identify a correspondence between the bright line whose image is captured by the first camera **5**L and the bright line whose image is captured by the second camera **5**R by using the image of the bright line whose image is captured by either one of the first and the second cameras and the three-dimensional plane. The advance preparation need not be performed for each measurement but may be achieved by only reading data stored in the storage apparatus **103** unless there is no change in the camera parameter **113**, the positional relationship between the stereo camera **5** and the pattern projector **7**, and the pattern of the pattern projector **7**.

Next, the three-dimensional measuring step S**3** in which the work **2** is actually measured will be described with reference to FIGS. **8** to **14**B. When three-dimensionally measuring the work **2**, first, the three-dimensional measuring apparatus **1** projects a plurality of slit lights **6** from the projector **7** onto the work **2** and captures images of the work **2** projected by the plurality of slit lights **6** by the first camera **5**L and the second camera **5**R. The control apparatus (arithmetic unit) **10** acquires the first and the second images **40** and **50** of the work **2** projected by the plurality of slit lights **6**, which are captured from the different positions (S**30** in FIG. **8**, image acquisition step). This image capturing may be performed once for each measurement.

When the control apparatus **10** acquires the first and the second images **40** and **50**, in the same manner as in the calibration of the light-section plane, the control apparatus **10** performs the distortion correction processing and the stereo images rectification processing on the first and the second images **40** and **50** (S**31** in FIG. **8**, correction step). Then, the control apparatus **10** detects the bright lines generated on the first image by the irradiation of the multi-slit light **6** and the bright lines generated on the second image by the irradiation of the multi-slit light **6** by using the corrected first and second images **40** and **50** (S**32** in FIG. **8**, bright line detection step).

When the control apparatus **10** detects the bright lines on the first and the second images, the control apparatus **10** selects one bright line from a plurality of bright lines on the first image (S**33** and S**34** in FIG. **8**, bright line selection step). The control apparatus **10** obtains a bright line on the second image and a light-section plane which correspond to the selected bright line on the first image (S**35** in FIG. **8**, step of identifying a set of corresponding bright lines). In summary, the control apparatus **10** functions as a bright line correspondence detection unit and identifies a correspondence between the bright line on the first image and the bright line on the second image by using the camera parameter **113** and the three-dimensional plane equation of the light-section plane regarding the bright lines detected from the captured images of the stereo camera **5** that captures images of the work **2**.

When one correspondence relationship among the bright line on the first image, the bright line on the second image, and the light-section plane is obtained, the control apparatus **10** obtains the above correspondence relationship regarding all the bright lines on the first image by using the same method (S**33** to S**37** in FIG. **8**).

When the correspondence relationships regarding all the bright lines are obtained (YES in S**37** in FIG. **8**), the control apparatus **10** obtains the three-dimensional position of the work **2** by the principle of triangulation by using one of the correspondence relationships among the bright line on the first image, the bright line on the second image, and the light-section plane. The control apparatus **10** obtains data of the three-dimensional shape of the work **2** by obtaining the three-dimensional position (S**38** in FIG. **8**).

Step of Identify Set of Corresponding Bright Lines

Next, the step of identifying a set of corresponding bright lines S**35** will be described in detail with reference to FIGS. **1** and **9** to **13**. In the description below, any one of a plurality of bright lines generated on the first image captured by the first camera **5**L by the irradiation of the slit light **6** is denoted by reference sign **4***j*. Also, any one of a plurality of bright lines generated on the second image captured by the second camera **5**R by the irradiation of the slit light **6** is denoted by reference sign **5***j*. Further, any one of a plurality of light-section planes of the slit light **6** is denoted by reference sign **6**Pj.

In the bright line selection step (S**33** and S**34** in FIG. **8**), when one bright line **4***j* is selected from a plurality of bright lines on the first image, the control apparatus **10** temporarily identifies a correspondence between the selected bright line **4***j* on the first image and one of a plurality of light-section planes (S**350** and S**351** in FIG. **9**, temporary identification step). In other words, the bright line **4***j* on a sensor surface (the first image) of the first camera **5**L, which is desired to correspond to a light-section plane, is assumed to be generated by the light-section plane **6**Pj which is the jth light-section plane (j is an arbitrary integer) of the light-section planes of the multi-slit light **6** stored in the storage apparatus **103**.

When a correspondence between the bright line **4***j* on the first image and the light-section plane **6**Pj is identified, the control apparatus **10** temporarily projects the selected bright line **4***j* on the first image onto the light-section plane **6**Pj, whose correspondence with the bright line **4***j* is temporarily identified, in a three-dimensional space as shown in FIG. **1** (S**352** in FIG. **9**, light-section plane projection step). After the control apparatus **10** projects the bright line **4***j* onto the light-section plane **6**Pj, the control apparatus **10** projects the bright line **4***j* on the first image onto the second image through the light-section plane **6**Pj (S**353** in FIG. **9**, second image projection step). In summary, the control apparatus **10** performs calculation processing for projecting the bright line **4***j* on the first image onto the assumed light-section plane **6**Pj in the three-dimensional space by using the three-dimensional plane equation of the light-section plane and the camera parameter and further projecting the projected bright line **4***j*P onto the second image (sensor surface of the second camera) **50**.

Next, the control apparatus **10** detects the bright line **5***j* on the second image nearest to a bright line **4***j*X on the first image which is projected onto the second image and calculates a level of similarity M between the bright line **4***j*X on the first image which is projected onto the second image and the bright line **5***j* on the second image (S**354** in FIG. **9**, level of similarity calculation step).

More specifically, as shown in FIG. **10**, the level of similarity M is evaluated by one or a combination of an average value **60**A of distances **60** in an epipolar constraint direction Y, an overlapped length **61** in a direction X perpendicular to the epipolar constraint, and distances **62***a* and **62***b* between end points. The epipolar constraint direction Y is the horizontal direction in an image corrected by the distortion correction and stereo images rectification processing. The level of similarity M may be evaluated by using a degree of similarity of image features (average intensity, contrast, and the like) around the bright line.

When the level of similarity M in one combination of the bright line **4***j* on the first image and the light-section plane **6**Pj whose correspondence is temporarily identified is calculated, the control apparatus **10** changes the light-section plane **6**Pj whose correspondence with the bright line **4***j* on the first image is identified. Then the control apparatus **10** repeats the processes from the temporary identification step S**351** to the level of similarity calculation step S**354** and calculates the level of similarity M of combinations of the bright line **4***j* and the light-section plane **6**Pj whose correspondence is newly identified.

The control apparatus **10** repeats the above processes, and when the degrees of coincidence M are obtained for combinations of the bright line **4***j* and all the light-section planes, the control apparatus **10** determines whether or not the bright line **4***j* on the first image and each light-section plane **6**Pj correspond to each other appropriately on the basis of the calculated degrees of coincidence M. Thereby, the control apparatus **10** determines a correct combination between the bright line **4***j* and the light-section plane **6**Pj (S**357**, determination step). Also, at this time, a correct combination of the bright line **5***j* on the second image, the bright line **4***j* on the first image, and the light-section plane **6**Pj is determined. The control apparatus **10** obtains correspondence relationships among the light-section plane **6**Pj, the bright line **5***j* on the second image, and the bright line **4***j* on the first image for all the bright lines **4***j* on the first image by the method described above.

In this way, the control apparatus **10** virtually projects the bright line **4***j* on the first image onto the second image through light-section plane **6**Pj and obtains the bright line **4***j*X on the first image which is projected onto the second image. The control apparatus **10** can determine a result of identified correspondence relationship among the bright line **4***j* on the first image, the light-section plane **6**Pj, and the bright line **5***j* on the second image by using the level of similarity M between the calculated bright line **4***j*X on the first image and the bright line **5***j* on the second image which is actually captured as an index.

More specifically, lines connecting the optical centers O_{5L} and O_{5R} of the first and the second cameras **5**L and **5**R and the bright lines **4***j* and **5***j* on the sensor surfaces **40** and **50** and the light-section plane **6**Pj of the slit light intersect each other in one line. When all the correspondence relationships among the bright line **4***j* on the first image, the light-section plane **6**Pj, and the bright line **5***j* on the second image are appropriate, these are a position of a bright line L formed when the work **2** is projected by the slit light.

The control apparatus **10** obtains an appropriate correspondence relationship among the bright line **4***j* on the first image, the bright line **5***j* on the second image, and the light-section plane **6**Pj by using the above relationships. When the bright line **4***j* on an image of one camera is projected onto the light-section plane **6**Pj and thereafter the projected bright line **4***j*P is further projected onto an image of the opposite side camera, there should be the bright line **5***j* whose position corresponds to the position of the further projected bright line **4***j*P on the image captured by the opposite side camera. Therefore, the above projection is performed on the light-section plane **6**Pj whose correspondence with the bright line **4***j* is temporarily identified and whether or not there is a corresponding bright line is determined, so that it is possible to determine whether or not the temporary identification of the light-section plane **6**Pj is appropriate.

According to the above method, it is possible to identify a correspondence between the bright lines **4***j* and **5***j* on the images and the light-section plane **6**Pj by a method other than the recognition of the bright lines by color, so that it is possible to perform three-dimensional measuring of a work to which a plurality of slit lights are projected by using a single color slit light pattern and by one-time image capturing.

Since a pattern light source of a single color can be used, it is possible to reduce the cost of the pattern light source. Further, since there is no intensity degradation of the light source by a color filter, it is not necessary to increase the intensity of the light source more than necessary. Furthermore, a high accuracy of pattern for preventing the bright lines of each color from overlapping each other is not required.

Since a monochrome camera can be used as the stereo camera **5**, higher sensitivity and higher definition can be realized compared with a case in which a color camera is required. In addition, since the three-dimensional measuring can be performed by one-time image capturing, it is possible to perform the measuring in a short time, so that a moving object on a production line can also be measured.

Other Possibility of identifying a Set of Corresponding Bright Lines

In the three-dimensional measuring of the work **2**, a bright line on an image generated by the same slit light may be divided and bright lines formed by different slit lights may be a connected bright line on the captured image due to unevenness of the shape of the work **2**, noise of the captured image, and the like. Therefore, when detecting the level of similarity M, if the divided lines are recognized or a bright line formed by different bright lines connected with each other is recognized as one bright line, the level of similarity M may not be detected correctly.

Therefore, when the control apparatus **10** calculates the level of similarity M, after identifying a correspondence between the bright line **4**jX on the first image and the bright line **5**j on the second image, the control apparatus **10** may divides the bright lines **4**jX and **5**j in a direction perpendicular to the epipolar constraint (bright line division step).

For example, a part of the bright line on the image may be divided as shown by the bright line **5**j in FIG. **11**(*a*) or may not be properly projected onto the image as shown by the bright line **4**jX. Therefore, after a correspondence between the bright lines **4**jX and **5**j is identified, as shown in FIG. **11**(*b*), regarding the both bright lines, the control apparatus **10** separates portions other than the portions **4**jX$_1$ and **5**j_1 that overlap each other in the direction perpendicular to the epipolar constraint and defines the separated portions as new bright lines **4**jX$_2$ and **5**j_2. The control apparatus **10** identifies a set of corresponding newly defined lines **4**jX$_2$ and **5**j_2 and calculates the level of similarity, so that the control apparatus **10** can correctly calculate the level of similarity M.

For example, in the case of FIG. **11**, the control apparatus **10** identifies a set of the corresponding overlapped portions **4**jX$_1$ and **5**j_1 of the bright lines which are originally selected and calculates the level of similarity M_1. Also, the control apparatus **10** identifies a correspondence between the separated bright line **4**jX$_2$ and a bright line **5**j_3 appearing on the second image as another bright line and calculates the level of similarity M_2. The control apparatus **10** may calculate the average of the calculated degrees of coincidence M_1 and M_2 to obtain the level of similarity M. Since the bright line **5**j_2 has no bright line whose correspondence with the bright line **5**j_2 is identified, so that a correspondence between the bright line **5**j_2 and any bright line is not identified.

In the embodiment described above, the level of similarity M is calculated for correspondence relationships between the bright line **4**j on the first image and all the light-section planes **6**Pj, and the correspondence relationship having the highest level of similarity M among a plurality of calculated degrees of coincidence M is defined as the appropriate correspondence relationship. However, as shown in FIG. **12**, when the level of similarity M is calculated, if the bright line **4**j on the first image is projected onto one of the light-section planes **6**Pj whose correspondence with the bright line **4**j is temporarily identified in the three-dimensional virtual space, the three-dimensional position at that time is obtained. As described above, the range in which the work **2** is located is set in advance. Therefore, if the three-dimensional position of the bright line **4**j when the bright line **4**j on the first image is projected onto one of the light-section planes **6**Pj whose correspondence with the bright line **4**j is temporarily identified is out of the three-dimensional range in which the work **2** is located, the control apparatus **10** may change the light-section plane **6**Pj whose correspondence with the bright line **4**j is identified without calculating the level of similarity M. In other words, the control apparatus **10** may have a level of similarity calculation determination step that determines whether or not to calculate the level of similarity M.

Specifically, in the case of FIG. **12**, the control apparatus **10** calculates the level of similarity M only for the third and the fourth light-section planes (intersection points P**3** and P**4**) where an intersection point (three-dimensional position) between the bright line **4**j on the first image and the light-section plane **6**Pj is within a range **70** in which the work **2** is located. The control apparatus **10** does not calculate the level of similarity M for the other light-section planes and completes the process after the light-section plane projection step (S**352** in FIG. **9**). By doing so, it is not necessary to calculate the level of similarity M for light-section planes that cannot be a candidate whose correspondence is identified, so that the amount of calculation is reduced and a correspondence of the bright line is quickly identified. Therefore, it is possible to shorten a measurement takt time.

Further, to perform the processing for identifying a correspondence of the bright line more quickly, light-section plane candidates whose correspondence with the bright line may be identified are stored for each area obtained by dividing the image or for each pixel. When a correspondence between the bright line and a light-section plane is identified, a correspondence between the bright line and only the light-section plane candidates corresponding to the position of the detected bright line on the image may be temporarily identified (light-section plane selection step).

Specifically, as described above, the positional relationship among the first camera **5**L, the second camera **5**R, and the projector **7** is calibrated in advance and the range **70** in which the work is located is set in advance. Therefore, as shown in FIG. **13**, it is possible to define what range of a range **80** on the first image **40** overlaps the range **70** in which the work is located in the virtual three-dimensional space. In other words, it can be said that the predetermined range **80** on the first image captures an image of an overlapped portion **90** with the range **70** in which the work is located on a three-dimensional virtual zone.

Also, the three-dimensional plane equation of the light-section plane **6**Pj of each slit light is known. Therefore, when the bright line **4**j is present in the range **80** on the first image in FIG. **13**, it can be said that the bright line **4**j is a bright line generated by one of the light-section planes **6**Pj$_3$ to **6**Pj$_5$ which pass through the overlapped portion **90**.

Therefore, as shown in FIG. **14**A, when the control apparatus **10** detects a bright line on the first image **40**, the control apparatus **10** creates a light-section plane search image (candidate index data **115**) in which a number of the light-section plane is recorded on pixels where a bright line on the image is present. As shown in FIG. **14**B, when the control apparatus **10** detects the bright line **4**j from the first image **40**, the control apparatus **10** may determine the light-section plane **6**Pj whose correspondence with bright line **4**j is temporarily identified by using the light-section plane search image **115**. The control apparatus **10** may create the light-section plane search image **115** for the second image and determine the light-section plane **6**Pj whose correspondence with bright line **4**j is identified when projecting the bright line **4**j on the first image onto the second image.

In summary, the control apparatus **10** temporarily identifies a correspondence between only the light-section planes that pass through a range, in which the predetermined three-dimensional range **70** in which the work is located and the three-dimensional range **80** corresponding to the range in which a bright line is present on the first image overlap each other, among a plurality of light-section planes, and the bright line on the first image. The control apparatus **10** may calculate the level of similarity M for the set of light-section planes whose correspondence with the bright line is identified.

In the embodiment described above, although a monochrome camera is used as the stereo camera **5**, a color camera may be used. A color light source may be used for the projector **7**. When the color camera and the color light source are used, it is possible to use a combination of the identification of the correspondence of the bright line by color and the identification the correspondence of the bright line of the present invention.

Further, the intervals of the slits of the projector **7** may be constant or may be inconstant. When a correspondence among the bright line **4***j* on the first image, the bright line **5***j* on the second image, and the light-section plane **6**Pj is identified, the three-dimensional measuring method may be any method that uses the principle of triangulation, such as the stereo method and the light-section method.

Further, although the three-dimensional measuring apparatus **1** may be used as a stand-alone three-dimensional measuring apparatus that measures a shape and orientation of an object, the three-dimensional measuring apparatus **1** may be included in an apparatus such as an automatic assembly robot, for example, the three-dimensional measuring apparatus **1** may be attached to the end of a robot arm.

Of course, the inventions described in the present embodiment, such as the bright line division step, the level of similarity calculation determination step, the light-section plane selection step, and the like, may be combined in any way.

While the present invention has been described with reference to exemplary embodiments, it is to be understood that the invention is not limited to the disclosed exemplary embodiments. The scope of the following claims is to be accorded the broadest interpretation so as to encompass all such modifications and equivalent structures and functions.

REFERENCE SIGNS LIST

1 Three-dimensional measuring apparatus
2 Work
4*j* Bright line generated on first image
5L First camera
5R Second camera
5*j* Bright line generated on second image
6X Slit light
6Pj light-section plane
7 Projector
10 Control apparatus

The invention claimed is:

1. A three-dimensional measuring apparatus comprising:

a projector configured to project slit light onto a work; a first camera configured to capture an image of the work projected by the slit light;

a second camera configured to capture an image of the work projected by the slit light from a position different from that of the first camera; and

a control apparatus configured to store a three-dimensional plane equation of a light-section plane of the slit light, identify a correspondence among a bright line generated on a first image captured by the first camera by projecting the slit light, a bright line generated on a second image captured by the second camera by projecting the slit light, and the three-dimensional plane equation of the light-section plane, and perform three-dimensional measuring of the work by a principle of triangulation by using a correspondence relationship among any of the bright line on the first image, the bright line on the second image, and the light-section plane,

wherein the control apparatus temporarily identifies a correspondence between the bright line on the first image and the light-section plane, temporarily projects the bright line on the first image onto the light-section plane in a three-dimensional virtual space, and thereafter projects the bright line onto the second image captured by the second camera through the light-section plane, and identifies a correspondence among the light-section plane and the bright lines on the images of the first and the second cameras on the basis of a level of similarity between the bright line on the first image which is projected onto the second image and the bright line on the second image.

2. The three-dimensional measuring apparatus according to claim **1**, wherein

the projector projects a plurality of slit lights onto the work, and the control apparatus temporarily identifies a correspondence between only the light-section planes that pass through a range, in which a predetermined three-dimensional range in which the work is located and a three-dimensional range corresponding to a range in which the bright line is present on the first image overlap each other, among a plurality of the light-section planes, and the bright line on the first image, and calculates the level of similarity.

3. The three-dimensional measuring apparatus according to claim **1**, wherein

if a three-dimensional position of the bright line when the bright line on the first image is projected onto one of the light-section planes whose correspondence is temporarily identified in a three-dimensional virtual space is out of a predetermined three-dimensional range in which the work is located, the control apparatus changes the light-section plane whose correspondence is to be identified without calculating the level of similarity.

4. A three-dimensional measuring method in which slit lights are projected from a projector onto a work and three-dimensional measuring of the work is performed by using a captured image of the work projected by the slit lights and three-dimensional plane equations of light-section planes of the plurality of slit lights, the method comprising:

an image acquisition step in which an arithmetic unit acquires a first image and a second image of the work projected by the plurality of slit lights, which are captured from different positions;

a step of identifying a set of corresponding bright lines in which the arithmetic unit determines an identification of a correspondence among each bright line on the first and the second images and the three-dimensional plane equations of the light-section planes; and

a measuring step in which the arithmetic unit performs three-dimensional measuring of the work by a principle of triangulation by using a correspondence relationship between any of the bright line on the first image, the bright line on the second image, and the light-section planes,

wherein the step of identifying a set of corresponding bright lines temporarily identifies a correspondence between each bright line on the first image and one of the light-section planes of the plurality of slit lights, temporarily projects the bright line on the first image onto the corresponding light-section plane in a three-dimensional virtual space, and thereafter projects the bright line onto the second image through the light-section plane, and determines whether or not the light-section plane and the bright lines on the first and the second images appropriately correspond to each other on the basis of a level of similarity between the bright line on the first image which is projected onto the second image and the bright line on the second image.

5. A non-transitory recording medium storing a program causing a computer to execute the steps of a three-dimensional measuring method in which slit lights are projected from a projector onto a work and three-dimensional measuring of the work is performed by using a captured image of the work projected by the slit lights and three-dimensional plane equations of light-section planes of the plurality of slit lights, the method comprising:

an image acquisition step in which an arithmetic unit acquires a first image and a second image of the work projected by the plurality of slit lights, which are captured from different positions;

a step of identifying a set of corresponding bright lines in which the arithmetic unit determines an identification of a correspondence among each bright line on the first and the second images and the three-dimensional plane equations of the light-section planes; and

a measuring step in which the arithmetic unit performs three-dimensional measuring of the work by a principle of triangulation by using a correspondence relationship between any of the bright line on the first image, the bright line on the second image, and the light-section planes,

wherein the step of identifying a set of corresponding bright lines temporarily identifies a correspondence between each bright line on the first image and one of the light-section planes of the plurality of slit lights, temporarily projects the bright line on the first image onto the corresponding light-section plane in a three-dimensional virtual space, and thereafter projects the bright line onto the second image through the light-section plane, and determines whether or not the light-section plane and the bright lines on the first and the second images appropriately correspond to each other on the basis of a level of similarity between the bright line on the first image which is projected onto the second image and the bright line on the second image.

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